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Real-Time In-Situ Measurement of Material Elastic Properties in a High Gamma Irradiation Environment

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REAL-TIME IN-SITU MEASUREMENT OF MATERIAL ELASTIC PROPERTIES IN A HIGH GAMMA IRRADIATION ENVIRONMENT

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ABSTRACT

The first measurements of elastic vibrations of an object in-situ to a high gamma irradiation field using a laser coupled resonant ultrasound method are described. A vibration mode of an Inconel hollow capped cylinder was measured throughout a period of 170 hours as the gamma radiation field was increased to 10^4 Gray/hour. The vibration mode frequency was observed to change in a manner consistent with the temperature dependence of the elastic stiffness coefficients of the material. These results illustrate the efficacy of the laser approach for real-time resonant ultrasound measurements in this severely hostile nuclear environment.

INTRODUCTION

Structural materials property data at operating temperature and as a function of duration in the high radiation field are needed for the next generation nuclear reactor design. Currently, since measurements cannot be made on-line while the sample remains in the reactor environment, it is necessary to place many samples in the reactor, remove one at the end of each desired interval and make measurements on those extracted samples off-line, usually within a "hot-cell". The current approach requires considerable time, exposure of personnel to radiation and may result in many samples that become radioactive waste. A better approach would be to place a single sample in the reactor for an extended period and make measurements at the desired time interval in-situ and in real-time. The goal of this work is to demonstrate the efficacy of making measurements on a sample in a reactor environment and follow changes in the material properties of the sample as a function of irradiation time. Elastic measurements on an Inconel sample located in a high gamma radiation field are reported here that show changes in the material elastic stiffness due to irradiation produced heating.

Ultrasonic NDE techniques have long been used to assess changes in industrial materials in less extreme environments. For instance, measurements have been reported on thermal aging/embrittlement in duplex stainless steels [1] and residual stress in steel [2]. Ultrasonic wave propagation has been used to observe changes in dislocation densities in aluminum [3] and microstructure stability due to cold work of Ti-modified austenitic stainless steel and other materials of interest to the nuclear community [4]. Vibrating sample internal friction measurements have identified the onset of plasticity in many materials [5]. Ultrasonic measurements have been extended through optical means to be noncontacting, offering the possibility of measurements in high radiation fields. The technique, known as Laser Ultrasonics, optically generates and detects acoustic waves of all types, is *noncontacting*, requires *no couplant* or invasive sample preparation and uses the *sample surface itself for transduction*. Consequently, laser techniques are highly predictable and quantitative.

Laser Resonant Ultrasound Spectroscopy (LRUS) was selected for the measurements reported here, see figure 1. LRUS produces simultaneous measurement of many vibration modes allowing determination of all of the elastic constants of the sample with a single measurement. Furthermore, the use of modern computational methods allows for accurate calculation of the resonant frequencies of an arbitrarily shaped sample of interest to the nuclear community. For a shape like the hollow capped cylinder used in this study, this computation can be performed on a PC in a reasonable time. This paper describes the first LRUS measurement of a hollow capped Inconel cylinder while it is located in a gamma radiation field of 10^4 Gray/hour. The design and construction of the sample positioning and laser light delivery and collection apparatus are described. Results are reported for totally noncontacting remote measurements of a split vibration mode over the course of 170 hours in the gamma radiation field.

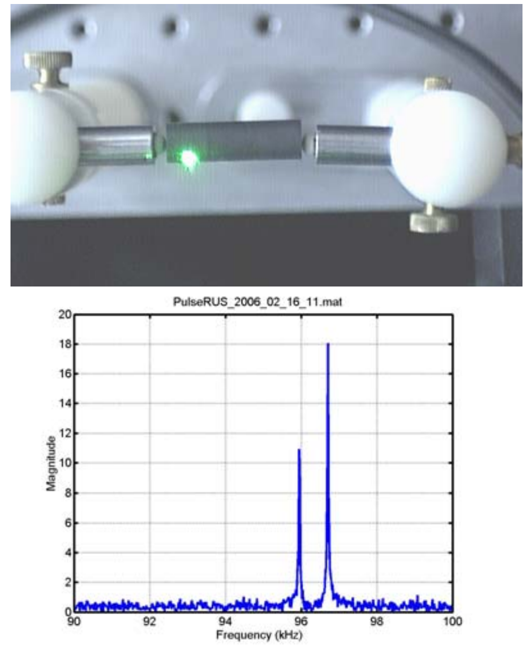

Figure 1. All optical noncontacting LRUS measurement of two resonant modes of a cylinder made through pulsed laser excitation (spot shown in top) and laser detection (spot not visible in top) along with the spectrum obtained (bottom).

LASER ULTRASONIC SETUP

The Advanced Test Reactor (ATR) at the Idaho National Laboratory has a Gamma Tube facility to provide a high gamma radiation experimental environment. It consists of a long empty tube with a sealed bottom that is oriented vertically and located near a fuel storage grid in the canal outside the reactor containment vessel. Fuel rods are loaded into the grid around the tube to provide the desired gamma radiation level. A pipe that allowed free space light propagation was constructed and installed in the ATR Gamma Facility Tube, with a sample holder and mechanical controls for positioning metallic mirrors for the experiment. Figure 2 shows the Laser Controlled Area and the pipe layout next to the canal area. Laser beams for both generation and detection of ultrasonic waves in the sample were directed into the top of the tube and reflected by mirrors through free-space to the bottom, ~ 10 meters from the laser equipment. At the bottom, a small concave mirror directed the source laser beam onto the sample surface. Also at the bottom, a second parabolic mirror focused the detection laser beam onto the sample and collected the scattered light. Both mirrors were metallic because radiation degrades glass. Full positioning control of the sample including insertion and extraction from the tube and all mirror orientations was designed into the top of the tube.

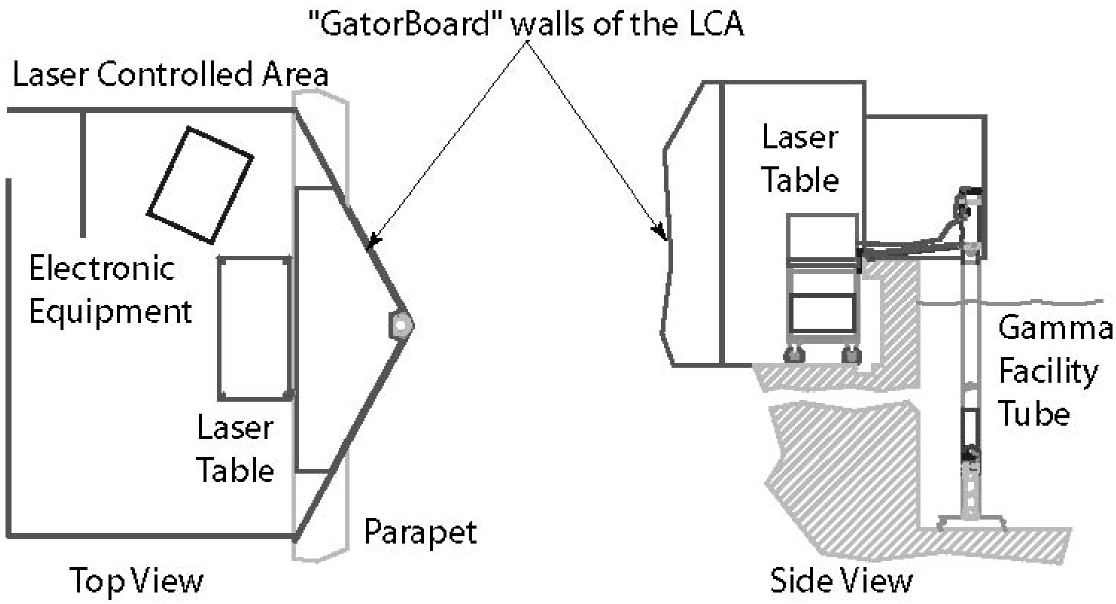

Figure 2. Schematic drawing of the LRUS setup showing the Laser Control Area (left) and the equipment installed in the canal area of the ATR (right). The walls consisted of a lightweight paper lined board "GatorBoard" that provided the required optical barrier while also being easy to construct and install.

An interferometric detection scheme, using a continuous Nd:YAG laser at 1064 nm, suitable for an industrial setting was constructed using a photorefractive system to demodulate the reflected light. The system measured the ultrasonic normal displacement motion of the sample surface. Photorefractive interferometers automatically adjust for environmental vibrations and can form interference with diffuse or multiple speckle reflection from the rough sample surface and require no stabilization feedback system. In spite of ongoing work in the canal area, no adverse effects from environmental vibrations were observed with the detection system during the test period. A pulsed Nd:YAG laser, producing approximately 1 millijoule, 7 ns duration pulses of 532 nm light at a repetition rate of 4-20 Hz, was used for vibration excitation.

The sample holder also included contact source and detection piezoelectric transducers as an aid for alignment of the laser beams as well as for a redundancy on the measurement setup. Although the two techniques, laser and piezoelectric, found several modes at the same frequencies, some modes were preferentially observed with one technique or the other due to different source and detector locations. A contact thermocouple also measured the temperature of the sample holder throughout the experimental run. The sample was an approximately 6.35 mm diameter by 25.4 mm long cylindrical tube with welded end caps of an Inconel material.

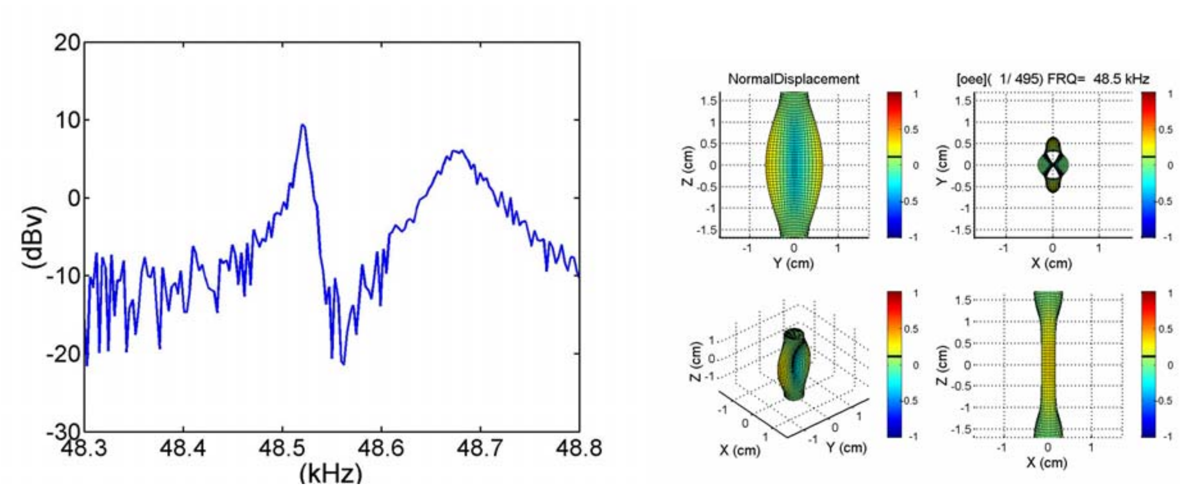

Figure 3. Spectrum of the mode used during the tests measured before fuel insertion (left). The mode shape (right) was predicted by the resonant ultrasound modeling to be that of the first "squeezed" mode that is doubly degenerate.

LASER RESONANT ULTRASOUND SPECTROSCOPY MEASUREMENTS

The measurement procedure consisted of exciting transient motion in the cylindrical sample through local heating. Sample "ringing" was recorded for periods up to 200 ms. Fourier transformation of the time sequence produced spectra of the vibration modes excited. The vibration frequencies of particular modes were calculated for the cylindrical tube sample with endcaps using the elementary XYZ basis function approach of Visscher et.al. [6]. The A_{00} two fold symmetric lateral squeezing mode was monitored for this study. Figure 3 shows the spectrum of this mode in more detail recorded in-situ before fuel was inserted around the Gamma Tube. This mode is split due to slight sample nonsymmetrical shape and the presence of the piezoelectric transducers touching the top corner along a diagonal. These two resonances were tracked as they changed frequency during and after fuel rods were placed adjacent to the Gamma Tube. At the start of the run, the radiation level was measured to be about 90 Gray/hr. After all the fuel elements were in place and the measurements had been completed (i.e. at the end of the 170 hour run) the radiation level was $>10^4$ Gray/hr. Although more resonant modes were observed in the sample, this experiment concentrated on these two modes and their dependence on time and temperature.

The available fuel elements were inserted near the Gamma Tube in three steps (approximately 1/3 at each step) and the resonances were recorded as a function of time. Both the temperature and resonance frequencies were observed to change markedly with the irradiation. Heating from the irradiation increased the temperature and decreased the vibration mode resonant frequencies. Figure 4 shows the measured temperature and resonant mode frequencies recorded over the course of first 50 hours during the experiment. The three fuel insertions are clearly seen as step increases in the temperature and decreases in the resonant frequencies. The temperature is seen to rise and then level off after each fuel insertion. Equilibrium was reached after approximately 1-2 hours when the heat flux due to irradiation was

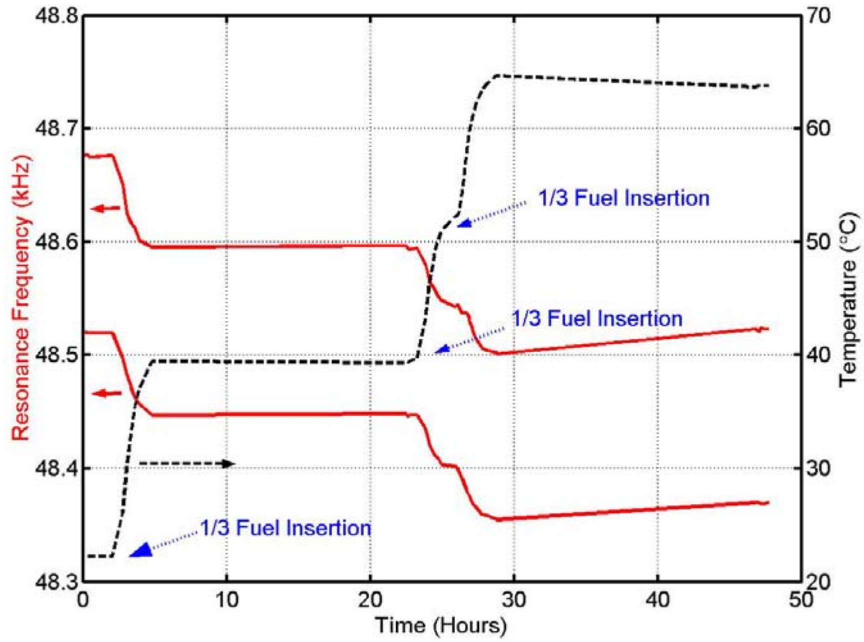

Figure 4. Time history of the sample temperature and resonant frequencies for the split A_{00} mode as the gamma irradiation was increased due to placing fuel rods closer to the Gamma Tube. Equilibrium plateaus result approximately 1-2 hours after each fuel insertion.

balanced by the heat leak to the canal water bath by conduction through the metal structures and air within the tube. The graph shows that the temperature increased from about 20 °C to about 65 °C during the fuel insertions. Correspondingly, the resonant mode frequencies decreased about 200Hz or 0.4% in a fashion that directly followed the changes in temperature. The observed A_{00} average mode frequency prior to irradiation was consistent with a Young's modulus of 179.0 GPa and Poisson's ratio of 0.308, which were used to predict the resonant mode frequencies. These values compare well with published values of 177.3 GPa and 0.308 at 20°C for Inconel 783 [7].

It was found that the resonant mode frequencies decreased linearly with temperature, as if the changes were due principally to sample heating from the irradiation, as expected. Changes in resonant mode frequency occur due to thermal expansion and accompanying reduction in density and also due to elastic stiffness temperature dependence. Modeling the A_{00} resonant mode frequency including only thermal expansion and subsequent density change has shown that this mode frequency would increase by about 10 Hz over the temperature range incurred, contrary to the decrease of frequency with temperature observed. However, including also the changes in Young's modulus and the shear modulus (or Poisson's ratio) for Inconel 783 from [7], the predicted A_{00} resonant mode frequency decreases with temperature at the rate of –4.8 Hz/°C which is comparable to the experimental value of –3.7 Hz/°C observed.

CONCLUSION

The first noncontacting measurements of mechanical properties of an object in-situ to a high gamma radiation field have been described. In-situ real-time measurements of acoustic/vibration motion of material parts during high irradiation are shown to be possible using laser excitation and detection. Frequency measurements of a split vibration mode of an Inconel hollow capped cylinder were performed continuously as the irradiation was increased to about 10^4 Gray/hour throughout a period of 170 hours. Theoretical modeling of the A_{00} vibration mode was performed which predicted that the mode frequency decreased with increasing temperature in a manner consistent with changes in the elastic moduli due to heating of the material under irradiation. These results illustrate the efficacy of the laser approach for real-time resonant ultrasound measurements in hostile nuclear environments.

ACKNOWLEDGMENTS

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